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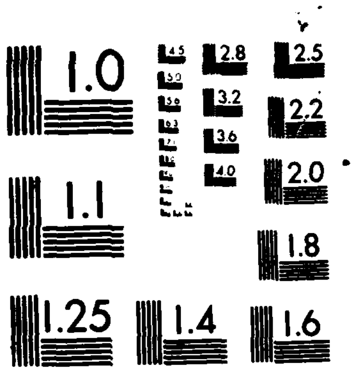

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This report briefly describes research results in nonlinear control theory obtained by the author and his students over the four-year period of support. The main focus of the research has been on a new approach for designing nonlinear control laws for nonlinear systems that is called design by extended linearization. Results reported include the development of this design method in regard to standard control problems, including linearized-system eigenvalue placement, input-output decoupling, and system inversion. Technical publications describing the results in detail are listed.

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Research on Nonlinear Control Theory

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Abstract

This report briefly describes research results in nonlinear control theory obtained by the author and his students over the four-year period of support. The main focus of the research has been on a new approach for designing nonlinear control laws for nonlinear systems that is called design by extended linearization. Results reported include the development of this design method in regard to standard control problems, including linearized-system eigenvalue placement, input-output decoupling, and system inversion. Technical publications describing the results in detail are listed.

1. Research Objectives and Accomplishments

The overall objective of this research effort was to make use of recent developments in the representation and realization theories for nonlinear systems to develop more effective analysis and design techniques for nonlinear control systems.

Since the current, standard method for design of nonlinear control systems is based on linearization of the nonlinear system about a constant operating point (equilibrium point), initial research toward the objective focused on the relationship of a nonlinear system to its family of linearizations about a range of constant operating points corresponding to a range of constant input values. Both Volterra series input-output representations and state equation representations were addressed in this investigation, and a number of relationships were deduced. From these relationships, it is sometimes possible to describe simply the information about the nonlinear system embodied in the family of linearizations, or to see how certain structural characteristics of the nonlinear system can be ascertained from the form of the linearized transfer function family. Also, it is easy to note various situations in which the linearization carries no useful information about the nonlinear system, in which case design based on the linearization is doomed. For example, the linearization transfer function can be zero at every constant operating point for non-trivial nonlinear systems. These results are reported in detail in [1-3], and [12].*

The second phase of the research involved trying to understand how the representation of a nonlinear system in terms of its family of linearizations might be used in a design setting. Using the linearization of a system at a single constant operating point as the basis for control-law design greatly restricts the range of validity of the design. Of course, the design process can be repeated at several constant operating points, and the resulting control laws can be pieced together by ad-hoc techniques. This so-called gain scheduling approach is ubiquitous in practice.

It was in the course of our efforts to understand and formalize the gain scheduling notion in terms of our work on families of linearizations that we devised a promising new design method. This method, which we call design by extended linearization, can be described as follows. (See [6, 7, 9].)

Design by extended linearization involves extending the notion of design based on linearized descriptions in the following way. Suppose that the nonlinear system to be controlled has a family of constant

* Numbers in square brackets refer to publications listed in Section 2 of this report.

operating points parameterized by constant input values. Then we can consider the corresponding parameterized family of linearized systems, and, for example, easily compute a family of linear state feedback gains that places the eigenvalues at specified values independent of the parameter. Finally, and this is the novel feature of the approach, this family of linear gains is 'realized' by a nonlinear state feedback gain. That is, a nonlinear gain is computed whose family of linearizations, corresponding to the closed-loop operating point, is precisely the designed family of linear gains. Thus, so long as the region of operation of the closed-loop nonlinear system remains in a neighborhood of <u>any</u> constant operating point in the family, the nonlinear system should exhibit the specified behavior.

This approach has a number of advantages, most following from the fact that the basis of the approach lies in (parameterized) linear design problems, and from the close connection to the gain-scheduling approach so heavily used in practice. Because of well-developed linear control methods, and the accompanying engineering intuition, the specification and achievement of a variety of performance objectives can be extended naturally to the nonlinear setting. This gives an avenue for addressing control problems ranging from the specification of closed-loop dynamics to structural problems such as input-output decoupling. Of course, the extended linearization method is local in the sense that objectives are guaranteed to be met only *in a neighborhood of the family* of closed-loop operating points. This means that nonlocal characteristics of the closed-loop system must be checked by simulation.

In the initial stages of this work, we considered control laws that were nonlinear functions of the state (or estimated state) but were linear in the command input. For multi-input systems, rather severe integrability conditions greatly complicated the process of determining nonlinear control laws from the designed, parameterized linear control law. Part of our effort went into demonstrating that for analytic multi-input systems the problem of eigenvalue scheduling for the family of closed-loop linearizations indeed can be solved. [11] That is, the integrability conditions mentioned above can be satisfied. However it turns out that this is not the case for other objectives, such as input-output decoupling, or linear-quadratic optimal control, that might be useful in the linear design process. These difficulties, and the complexity of our existence result in regard to developing a design procedure, led to the consideration of a more general class of nonlinear control laws. Namely, instead of considering control laws that are linear in the command input and nonlinear in the state (or, estimated state), consider control laws that are nonlinear in both. This has lead to a natural and efficient solution to the problems above, where analyticity is not required, and the theory can be effectively implemented in a design process. This work has been reported in [12] and [13], and it is shown that input-output decoupling incorporating pole placement in the closed-loop linearized system can be addressed in the

more general framework. In fact, both state-feedback and output-feedback results from the linear case can be extended to the nonlinear setting.

A related theoretical effort involved applying the basic ideas of design by extended linearization to the problem of designing inverses for nonlinear, dynamic systems. This problem has important applications, for example in robot path planning, and in distortion cancellation problems in communications. Our results show that, in the single-input case, the extended linearization idea avoids a some technical difficulties associated with the exact inversion theory, applies to a wider class of systems, and yields a 'partial inverse system' that performs well over a reasonable portion of the operating range of the system. This work is reported in [8].

In the course of the research effort, a number of simple examples were addressed to demonstrate the method. One is the pendulum balancer in [6]. Also, it is shown in [14] that classical, linear process control design rules can be applied to nonlinear plants via extended linearization, and standard noninteracting-tank examples are given. Finally, we have worked on the problem of designing a nonlinear, output-feedback control law for a (4-state, pitch-axis) nonlinear flight control model. [10] This exercise has demonstrated that the method of design by extended linearization is feasible to apply to nontrivial examples using modern symbolic computation capabilities such as provided by MACSYMA. Furthermore, the nonlinear designs produced do control the local dynamical behavior of the closed-loop system over a wide operating range.

At this point in time, it seems clear that the extended linearization design approach will be an important tool for the future. It is a direct method that permits the designer to address the control problem in terms of the natural description of the plant, i.e., nonlinear variable changes to a canonical form are not required. Also, the well-established methods and intuitions associated with linear control design form the basis for the approach to the nonlinear design problem. Finally, the computations involved are well within the current capabilities of symbolic manipulation programs. This is not to say that there aren't important issues for further study. For example, further work on the nonuniqueness of nonlinear control laws arising from the method in regard to nonlocal properties of the resulting closed-loop system is of immediate importance in furthering the development of the approach. The claim is, rather, that a good foundation has been set.

2. Publications

(1 March 1983 -- 28 February 1987)

[1] R. Lejeune and W. J. Rugh, "Linearization of Discrete-Time Polynomial Systems About Constant Operating Points," Proceedings of the 17th Annual Conference on Information Sciences and Systems, The Johns Hopkins University, Baltimore, MD, pp. 422-426, 1983.

[2] W. J. Rugh, "Linearization About Constant Operating Points: An Input-Output Viewpoint," Proceedings of the 22nd IEEE Conference on Decision and Control, San Antonio, TX, pp. 1165-1169, 1983.

[3] R. Lejeune and W. J. Rugh, "Linearization of Nonlinear Systems About Constant Operating Points," IEEE Transactions on Automatic Control, Vol. AC-30, No. 8, pp. 804-808, June, 1984.

[4] W. J. Rugh, "An Input-Output Characterization for Linearization by Feedback," Systems and Control Letters, Vol. 4, No. 4, pp. 227-229, June, 1984.

[5] W. J. Rugh, "Design of Nonlinear Compensators for Nonlinear Systems by an Extended Linearization Technique," Proceedings of the Twenty-Third IEEE Conference on Decision and Control, Las Vegas, NV, pp. 69-73, December 1984.

[6] W. T. Baumann and W. J. Rugh, "Feedback Control of Nonlinear Systems by Extended Linearization," IEEE Transactions on Automatic Control, Vol. AC-31, No. 1, pp. 40-46, 1986.

[7] W. T. Baumann and W. J. Rugh, "Feedback Control of Nonlinear Systems by Extended Linearization: The Multi-Input Case," Theory and Applications of Nonlinear Control Systems, C. Byrnes, A. Lindquist, eds., North-Holland, Amsterdam, The Netherlands, pp. 107-113, 1986.

[8] W. J. Rugh, "An Extended-Linearization Approach to Nonlinear System Inversion," accepted for publication, IEEE Transactions on Automatic Control, Vol. AC-31, No. 8, pp. 725-733, 1986.

[9] W. J. Rugh, "The Extended-Linearization Approach for Nonlinear System Problems," Nonlinear Control and System Theory, M. Fliess, M. Hazewinkel, eds., D. Reidel Publishing Co., Dordrecht, Holland, pp. 285-309, 1986.

[10] W. T. Baumann, J. L. Wang, W. J. Rugh, "Application of the Extended Linearization Design Method to Longitudinal Flight Control," Proceedings of the Twenty-Fourth IEEE Conference on Decision and Control, Ft. Lauderdale, FL, p. 1653, December, 1985. (Full version in Technical Report JHU/EECS - 85/19, Department of Electrical Engineering and Computer Science, The Johns Hopkins University.)

[11] W. T. Baumann, W. J. Rugh, "Feedback Control of Analytic Nonlinear Systems by Extended Linearization," SIAM Journal on Control and Optimization, accepted for publication, 1987.

[12] J. L. Wang, W. J. Rugh, "On Parameterized Linear Systems and Linearization Families for Nonlinear Systems," IEEE Transactions on Circuits and Systems, accepted for publication, 1987.

[13] J. L. Wang, W. J. Rugh, "Feedback Linearization Families for Nonlinear Systems with Applications to Input-Output Decoupling," submitted for publication, 1987.

[14] W. J. Rugh, "Design of Nonlinear PID Controllers," submitted for publication, 1987.

3. Personnel

Principal Investigator:

Wilson J. Rugh: Professor of Electrical and Computer Engineering

Research Assistants (Graduate Students):

William T. Baumann: BS, Lehigh University; MS, M.I.T.; PhD Fall 1985. Dissertation Title: "Feedback Control of Nonlinear Systems by Extended Linearization" (Current Position: Assistant Professor of Electrical Engineering, Virginia Polytechnic Institute and State University.)

Jian-Liang Wang: BS, Beijing Institute of Technology; MS, Johns Hopkins University, 1985; PhD expected, August 1987. Tentative Dissertation Title: "The Extended-Linearization Design Method"

Roland Lejeune: BS, Ecole Centrale des Arts et Metiers, Belgium; MS, University of Virginia.

Judith E. Blank: BA, University of Chicago (Deceased).

4. Interactions

Presentations of the publications in Section 2 during the period 1 March 1983 -- 28 February 1987 are as follows.

[1] was presented at the Conference on Information Sciences and Systems, Baltimore, MD, on 24 March 1983.

[2] was presented as an invited paper at the IEEE Conference on Decision and Control, San Antonio, TX, on 15 December 1983.

[3] was presented at a research seminar in the Department of Electrical Engineering, University of Maryland, College Park, MD, on 8 March 1983.

[4] was presented at the Conference on Information Sciences and Systems, Princeton, NJ, on 15 March 1984.

[5] was presented at a research seminar, IBM Watson Research Center, Yorktown Heights, NY, on 12 July 1984; and at the IEEE Conference on Decision and Control, Las Vegas, NV, on 12 December 1984.

[6] was presented at a research seminar in the Department of Electrical Engineering and Computer Science, Princeton University, Princeton, NJ, on 25 September 1984, a research seminar in the Department of Mathematics, Virginia Polytechnic Institute and State University, Blacksburg, VA, October 1985, and at the Conference on Information Sciences and Systems, Baltimore, MD, March, 1985.

[7] was presented at the Seventh Annual Symposium on the Mathematical Theory of Networks and Systems, Stockholm, Sweden, June, 1985.

[8] was presented at the Workshop on Geometric Control Theory, Paris, France, June, 1985.

[9] was presented at a research seminar in the Division of Engineering, Brown University, Providence, RI, December, 1985.

[10] was presented at the IEEE Conference on Decision and Control Theory, Ft. Lauderdale, FL, December, 1985.

[12] was presented at the Conference on Information Sciences and Systems, Princeton, NJ, 1986.

In addition, Wilson J. Rugh visited Wright-Patterson AFB, Ohio, on 23 January 1985, where he met with Mr. Charles Suchomel, and others, of AFWAL/FIGC, and Professors D'Azzo, Houpis, Jones, and others, of AFIT. The subject of this visit was a nonlinear flight control model to be used as a test case for the application of the extended-linearization design method. Interaction with Mr. Suchomel continued through the course of development of [10].

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